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SIMULATED AIRLINE SERVICE EXPERIENCE WITH LAMINAR-FLOW CONTROL LEADING-EDGE SYSTEMS

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SUMMARY

Achieving laminar flow on the wings of a commercial transport involves difficult problems associated with the wing leading edge. The NASA JetStar Leading Edge Flight Test Program has made major progress toward solution of these problems. Effectiveness and practicality of laminar-flow leading edge systems were proven under representative airline flight conditions. This was accomplished in a series of simulated airline service flights by modifying a JetStar aircraft with laminar-flow control leading-edge systems and operating it out of three commercial airports (Atlanta-Hartsfield, Greater Pittsburgh International, and Cleveland-Hopkins International) as an airline would under actual air traffic conditions, bad weather, and insect infestations. About 62 flights to 33 domestic airports were made during severe summer and winter weather.

Two different leading-edge test articles were flown. One used suction through approximately 1 million 0.0025 inch diameter electron-beam perforated holes in titanium skin to maintain laminar flow on the test article upper surface. A Krueger-type flap served as a protective shield against insect impact. The test article also contained cleaning, deicing, and purging systems. The second test article used suction through 27 narrow spanwise slots (about 0.004 inch wide) on both upper and lower titanium surfaces.

LEFT JETSTAR SIMULATED AIRLINE SERVICE

The JetStar Leading Edge Flight Test (LEFT) aircraft is shown in figure 1 being serviced during the Simulated Airline Service (SAS) flight test segment based at Pittsburgh, September 13, 1985. The objective of the SAS program was to obtain operational data on practical laminar-flow control (LFC) leading-edge systems in the commercial airline environment. Summaries of laminar-flow control definition studies are available in references 1-5. References 6-9 provide complete descriptions of the LEFT test articles development program. LFC structural design details are given in references 10-13. Meteorological data are summarized in references 14-16.

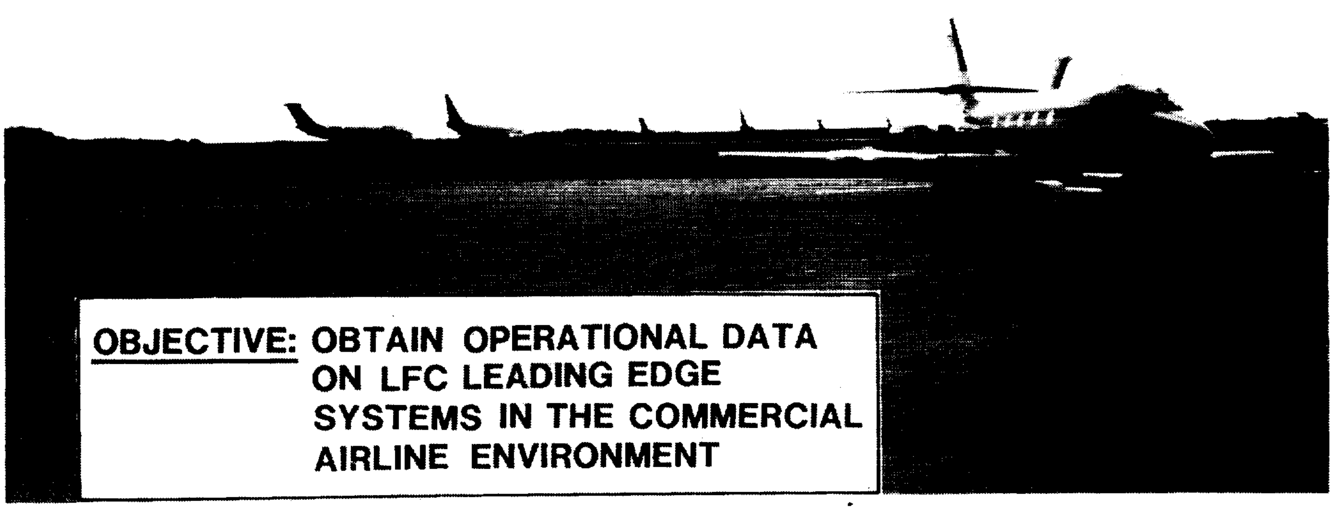
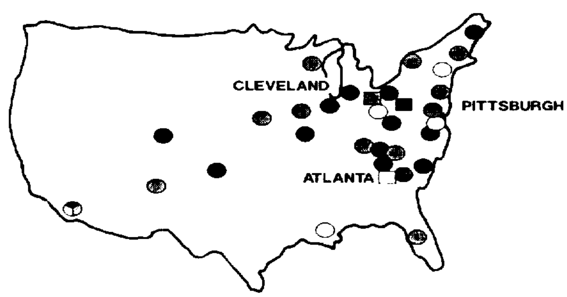


Figure 1

SIMULATED AIRLINE SERVICE FLIGHTS

During the simulated airline service, one to four flights per day were made from three "home base" United States airports (Atlanta, Pittsburgh, and Cleveland). From these three major airports, a total of 62 SAS flights to 33 airports were made (figure 2). Seasonal data were obtained with the Atlanta flights in July, the Pittsburgh flights in September, and the Cleveland flights in February. Thus, the weather conditions experienced varied from extreme summer to severe winter. The SAS flights were preceded by flight tests designed to shake-out the airplane and its systems, and to determine a nominal suction level for the SAS flights (ref. 9). In addition, a pre-cursor airline type flight series was made throughout the western United States for which the JetStar was based at the NASA Ames/Dryden Flight Research Facility (ref. 9). Thus, the SAS and the associated Dryden based flights fairly simulated airline service throughout the domestic United States.



HOME BASE	DATE	FLIGHTS
ATLANTA	JULY 85	BASED AT 3 MAJOR AIRPORTS
PITTSBURGH	SEPT. 85	FLOWN IN/OUT 33 AIRPORTS
CLEVELAND	FEB. 86	62 FLIGHTS MADE

Figure 2

JETSTAR SIMULATED AIRLINE SERVICE

A summary of the SAS flight number, date of flight, airport, and cruise time is provided in figure 3. More than 39 hours of cruise data were obtained. Block time was over 60 hours.

BASE	FLIGHT	DATE	FROM	TO	CRUISE TIME, HRS
ATLANTA	1059	07/15/85	EDW	AMA	0.64
(13 FLIGHTS)	1060	07/15/85	AMA	BAD	0.43
	1061	07/15/85	BAD	ATL	0.47
	1062	07/16/85	ATL	STL	0.82
	1063	07/16/85	STL	ATL	0.36
	1064	07/17/85	ATL	CLE	0.50
	1065	07/17/85	CLE	SPI	0.73
	1066	07/17/85	SPI	ATL	0.60
	1067	07/18/85	ATL	MSY	N.A.
	1068	07/18/85	MSY	ATL	N.A.
	1069	07/20/85	ATL	ORF	0.38
	1070	07/20/85	ORF	ATL	0.37
	1071	07/22/85	ATL	LFI	0.49
PITTSBURGH	1079	09/09/85	EDW	DEN	0.95
(26 FLIGHTS)	1080	09/09/85	DEN	STL	0.83
	1081	09/09/85	STL	PIT	0.47
	1082	09/10/85	PIT	BOS	0.50
	1083	09/10/85	BOS	PIT	0.55
	1084	09/11/85	PIT	ORD	0.33
	1085	09/11/85	ORD	CHA	0.47
	1086	09/11/85	CHA	PIT	0.40
	1087	09/12/85	PIT	BNA	0.62
	1088	09/12/85	BNA	CLE	0.50
	1089	09/12/85	CLE	PIT	0.53
	1090	09/13/85	PIT	CHS	0.52
	1091	09/13/85	CHS	DCA	0.39
	1092	09/13/85	DCA	PIT	0.52
	1093	09/14/85	PIT	DET	0.41
	1094	09/14/85	DET	PIT	0.64
	1095	09/16/85	PIT	BGR	0.67
	1096	09/16/85	BGR	JFK	0.33
	1097	09/16/85	JFK	RDU	0.43
	1098	09/16/85	RDU	PIT	0.50
	1099	09/17/85	PIT	AZO	0.51
	1100	09/17/85	AZO	PIT	0.50
	1101	09/18/85	PIT	STL	0.80
	1102	09/18/85	STL	OKC	0.60
	1103	09/18/85	OKC	ABQ	0.53
	1104	09/18/85	ABQ	EDW	0.70
CLEVELAND	1131	02/19/86	EDW	AMA	1.17
(23 FLIGHTS)	1132	02/19/86	AMA	SPI	0.99
	1133	02/19/86	SPI	CLE	0.56
	1134	02/20/86	CLE	ATL	0.66
	1135	02/20/86	ATL	ACY	1.07
	1136	02/20/86	ACY	CLE	0.63
	1137	02/21/86	CLE	BOS	0.62
	1138	02/22/86	BOS	CLE	1.03
	1139	02/24/86	CLE	TYS	0.59
	1140	02/24/86	TYS	TPA	0.75
	1141	02/24/86	TPA	BNA	0.97
	1142	02/24/86	BNA	CLE	0.62
	1143	02/25/86	CLE	GRB	0.65
	1144	02/25/86	GRB	LOU	0.53
	1145	02/25/86	LOU	CLE	0.76
	1146	02/26/86	CLE	BTV	0.73
	1147	02/26/86	BTV	LFI	0.81
	1148	02/26/86	LFI	CLE	0.75
	1149	02/27/86	CLE	RIC	0.85
	1150	02/27/86	RIC	CLE	0.83
Total Cruise	1151	02/28/86	CLE	DSM	0.96
Time Hours = 39.08	1152	02/28/86	DSM	DEN	1.11
	1153	02/28/86	DEN	EDW	1.45

Figure 3

JETSTAR FLIGHT SCHEDULE

An example of the Jetstar flight schedule for February 24, 1986, during the Pittsburgh based simulated airline service, is presented in figure 4. Four airline-type flights were made on this day. Aircraft turn-around time was about 1.5 hours. Flights included airline simulation of service during peak traffic hours.

FLIGHT	DATE	TIME	LOCATION	WEATHER
1139	2/24/86	8:32 AM 9:46 AM	CLEVELAND, OH KNOXVILLE, TN	26° F, OVERCAST
1140	2/24/86	10:42 AM 12:05 PM	KNOXVILLE, TN TAMPA, FL	41° F, RAIN
1141	2/24/86	1:04 PM 2:42 PM	TAMPA, FL NASHVILLE, TN	70° F, SCATTERED CLOUDS
1142	2/24/86	3:25 PM 4:41 PM	NASHVILLE, TN CLEVELAND, OH	40° F, OVERCAST

Figure 4

GROUND RULES

The LEFT JetStar SAS flights were made as similar to commercial transport airplane operation as was possible (figure 5). This included scheduled take-offs and landings; queuing up with commercial airliners; use of air traffic control of vector, altitude, and speed; operation at various times of day including peak traffic hours; before, during, and after flight exposure to the same atmospheric conditions as experienced by the transport airplanes; and overnight outdoor parking. LFC systems were operated in a "hands-off" mode with no adjustments permitted during flight (i.e. the same suction control settings were used for all flights). The LFC suction system was operated in an on/off mode.

GROUND RULES

- **OPERATED LIKE AIRLINE WOULD**
  - **SCHEDULED DISPATCH**
  - **QUEUE UP WITH OTHER AIRLINES**
  - **ATC SYSTEM**
  - **PEAK TRAFFIC HOURS**
- **OVERNIGHT APRON PARKING**
- **EXPOSED TO ELEMENTS**
- **ON/OFF LFC SYSTEMS OPERATION**

Figure 5

EVALUATION OF LFC SYSTEMS

Five laminar flow control systems were used on the LEFT JetStar aircraft and evaluated during the simulated airline service flights. These five systems are the suction, high-lift/shield, wetting, purge, and anti-icing systems (figure 6). The suction system removes a small amount of the laminar boundary layer through either surface perforations or slots. This controls growth of boundary layer disturbances and thus delays transition of the boundary layer from laminar to turbulent flow.

The suction surfaces include both a perforated and a slotted test article, one on each wing. The perforated suction surface test article, designed and built by the Douglas Aircraft Company (DAC), maintains laminar flow on the upper surface of the right wing to the front spar (ref. 7). The front spar is located at about 14 percent chord. Suction is obtained through approximately 1 million 0.0025 inch diameter electron-beam drilled holes in titanium skin. A retractable Krueger-type shield is used as the primary insect contamination avoidance device, and provides line-of-sight protection against insect impingement. Normally, the shield would also serve as a high-lift leading-edge device. For this flight program, however, safety considerations dictated that the shield be deliberately designed for very little high lift production. The supplemental freezing-point depressant, Propylene Glycol Methyl Ether (PGME), sprayed on the wing upper surface from nozzles mounted underneath the shield, wets the suction surface and provides additional protection against insect adhesion and icing. When no insects are present, as at Cleveland in the winter, neither the shield nor the wetting system is needed for insect protection. Anti-icing systems were evaluated during the Cleveland service.

The slotted suction surface test article, built by the Lockheed-Georgia Company (LAC), is designed to maintain laminar flow to the front spar on both upper and lower wing suction surfaces and therefore has no leading edge shield (ref. 6). Suction is attained through 27 spanwise slots about 0.004 inch wide. Wetting the wing leading edge region with the freezing-point depressant (ejected through surface slots during insect encounters) is the means used for preventing insect accumulation (refs. 1, 2). This fluid system also provides the anti-icing function.

To prevent clogging of the perforations or surface slots by the wetting fluid, both concepts require a purging system that clears the LFC passages by pressurizing the subsurface and thus removing the PGME fluid from the LFC ducts and surface.

Operational experience with these five LFC systems was obtained at varying geographical location, season, cruise altitude, and speed.

	ATLANTA	PITTSBURGH	CLEVELAND
SUCTION	YES	YES	YES
HI-LIFT/SHIELD	YES	YES	NO
WETTING	YES	YES	NO
PURGE	YES	YES	YES
ANTI-ICING	NO	NO	YES

Figure 6

DOUGLAS INSECT/ICE PROTECTION SYSTEM IN FLIGHT

The Douglas perforated test article insect and ice protection system in flight use is shown in figure 7. In the Douglas concept for a full wing (ref. 2), laminar flow is attained only on the upper surface which contributes nearly two-thirds of the wing friction drag and thus two-thirds of the potential net drag reduction. Elimination of the lower surface suction systems and the associated stringent LFC surface smoothness requirements then permits use of the Krueger-type leading edge insect protection shield and high lift device stored in the lower surface of the leading edge during cruise. Spray nozzles are mounted on the Krueger underside to supplement, if needed, the insect protection capability of the shield, or to provide the PGME freezing-point depressant fluid for leading edge anti-icing. A system for purging fluid from the suction flutes and surface perforations is also provided. Shield leading edge anti-icing is obtained through use of a commercially available system manufactured by TKS, Ltd.

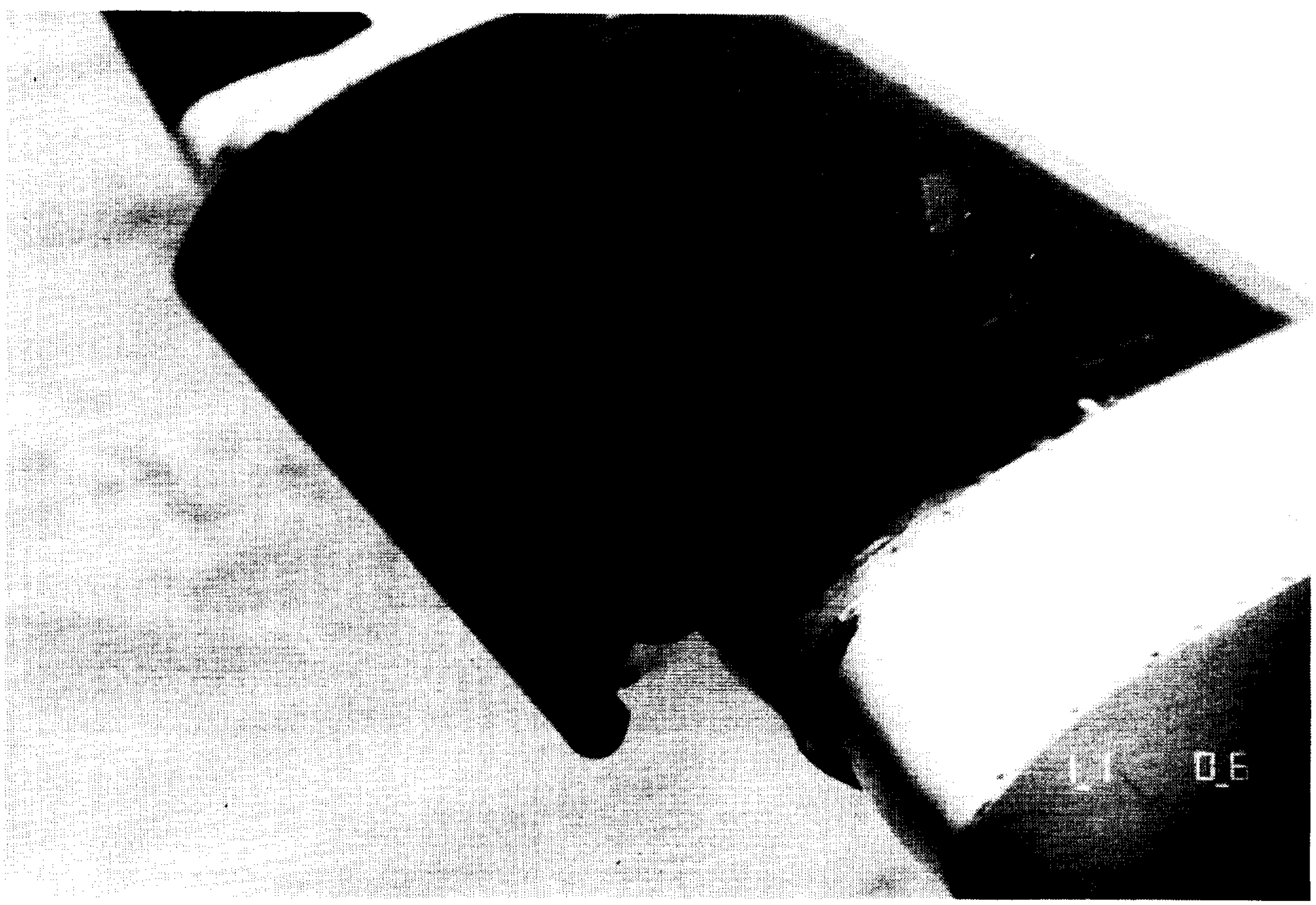


Figure 7

LOCKHEED INSECT/ICE PROTECTION SYSTEM IN FLIGHT

The Lockheed slotted test article insect and ice protection system in flight use is shown in figure 8. Laminar flow is obtained on both top and bottom surfaces (refs. 1,6). Six slots in the leading edge region provide the fluid film for both insect protection and anti-icing. To purge this fluid, pressurized air is forced through the slots during climbout after which these slots are also used for suction to laminarize the boundary layer.

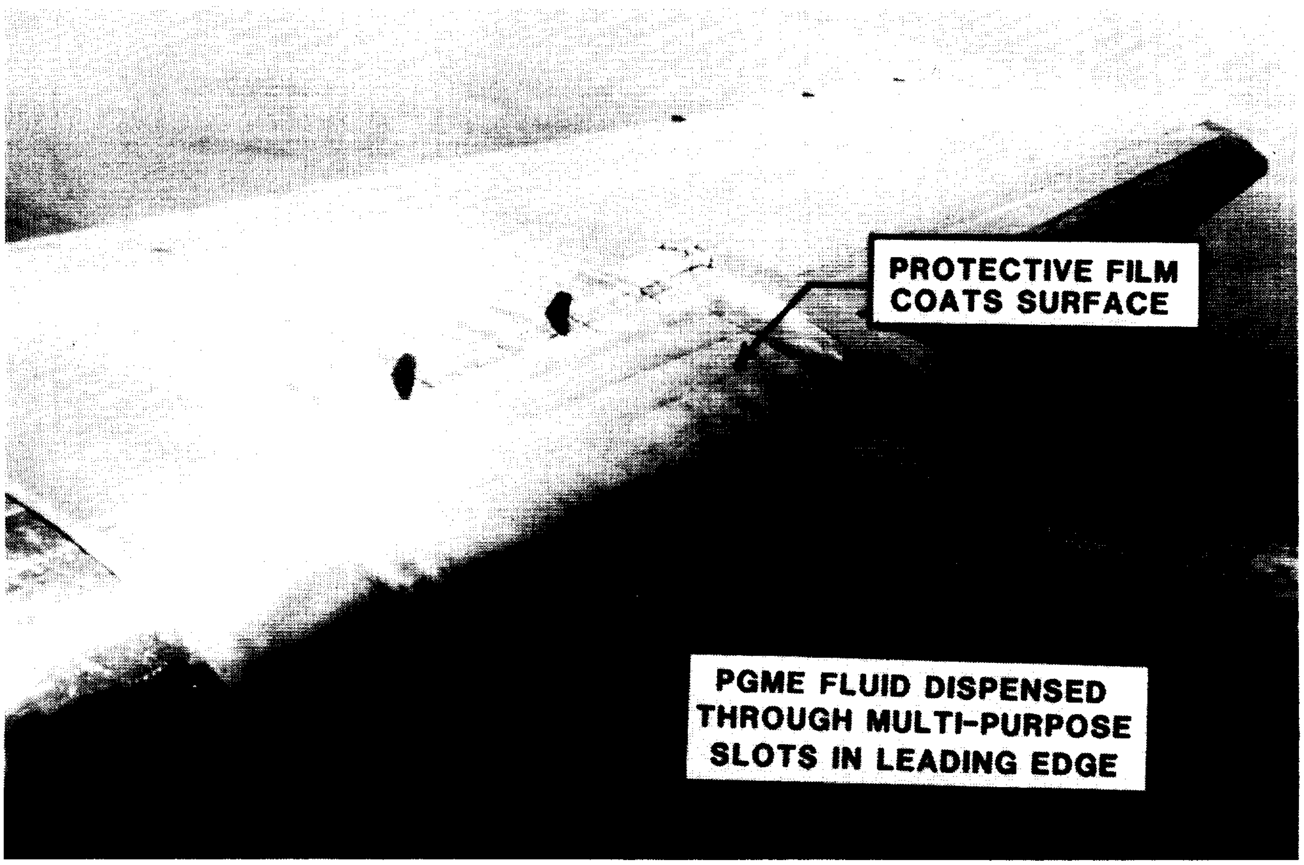


Figure 8

INSECT CONTAMINATION - BOSTON TO PITTSBURGH

Figure 9 indicates how bad insect deposits can be during a flight descent in other than winter conditions. Flight 1083 was made September 10, 1985, from Boston to Pittsburgh. Insects accumulated on the Lockheed test article during descent only when the anti-contaminant fluid was not ejected. Simple cleaning of the slotted test article leading edge region with a damp cloth was therefore necessary before every non-winter SAS flight. The anti-contaminant fluid was almost 100% effective in eliminating insect contamination on the slotted test article in takeoff and climb.

The Krueger shield on the Douglas test article could be used during descent as well as ascent and was almost completely effective in eliminating bug hits. The occasional insect deposits that did occur at the inboard end of the shield would be eliminated with a more effective design. The Atlanta SAS flights showed that the perforated article did not have to be cleaned after each flight. Beginning with Flight 1071, therefore, the perforated test article was not cleaned before each flight. It was also noticed that insect debris tended to erode away with time, and that passing through cloud cover allowed a natural washing of the surface. Partway through the Pittsburgh simulated service, it was found that the shield alone was sufficient to protect the perforated test article from insects. Use of the anti-contaminant fluid was discontinued from that point onward; a definite need for supplemental anti-contaminant spray, therefore, could not be established - provided the configuration includes a properly designed insect protection/high-lift device. The perforated article took only 5 insect hits during the entire simulated airline service flights; all 5 hits were inboard near the locations shown in figure 9.

Should the suction surfaces eventually clog after long service, the test articles can be steam-cleaned (ref. 2). This cleaning method was demonstrated on one occasion after months of flight testing at Ames-Dryden, even though no change in surface porosity, evidence of clogging, or need for cleaning was evident as a result of flight service. The entire simulated airline service flight program was conducted over a period of 7 months with no need for steam cleaning.

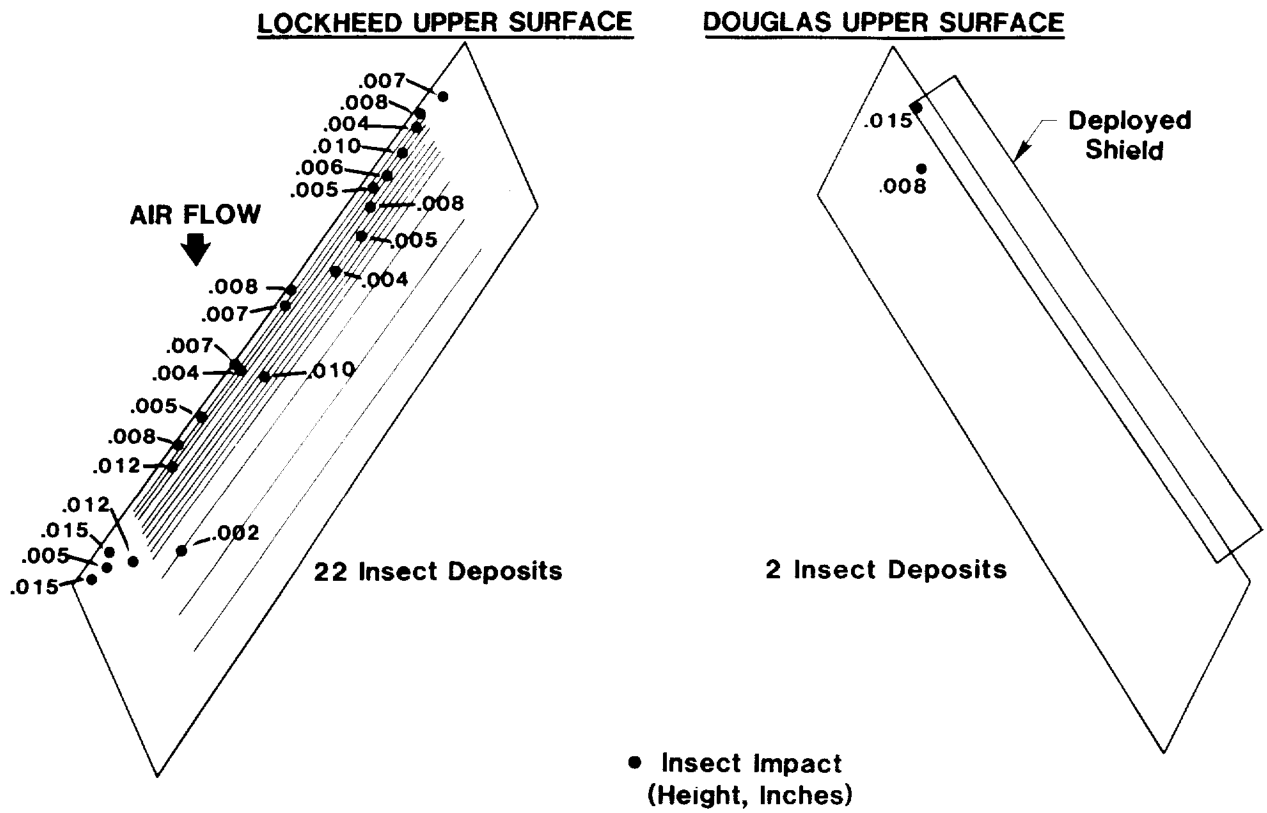

LOCKHEED UPPER SURFACE
DOUGLAS UPPER SURFACE
AIR FLOW
.007
.008
.004
.010
.006
.005
.008
.005
.004
.008
.007
.007
.004
.010
.005
.008
.012
.012
.015
.005
.015
.002
22 Insect Deposits
.015
.008
Deployed Shield
2 Insect Deposits
Insect Impact (Height, Inches)

Figure 9

SIMULATED AIRLINE SERVICE WINTER CONDITIONS

Figures 10-12 show the severe snow and ice accumulation on the airplane after it was left out overnight during winter conditions in the simulated service flights based at Cleveland during February, 1986.

Figure 10

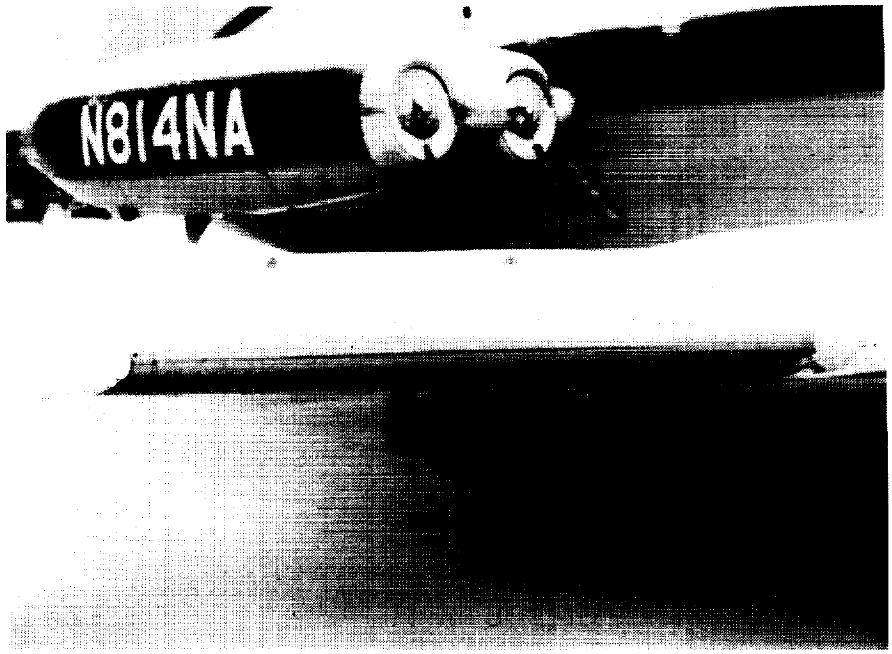


Figure 11

Figure 12

DEICING ON GROUND

Ground deicing of the LFC test articles was no more difficult than normal deicing of commercial transports. Snow and ice accumulation was easily eliminated with the hand-held deicing equipment shown in figure 13. This photo was taken before takeoff from Cleveland, February 21, 1986. Use of the anti-icing fluid on the test articles in flight was previously shown in figures 7 and 8.

Figure 13

Results shown in figure 14 indicate long periods of steady amounts of laminar flow in clear air. Figure 14 also shows a large forward movement in transition location and consequent loss of laminar flow when flying through clouds (see t = 28 and 30 min.). The data are from flight 1135 from Atlanta to Atlantic City on February 20, 1986. Cloud penetration is indicated by an increase in airplane electrical charge as measured by the charge patch instrument mounted on the leading edge of the plyon. The plyon is located on the top of the JetStar fuselage. Charge indicator results were correlated with ice particle measurements using the Knollenberg probe mounted on top of the plyon. Detailed meteorological results on laminar flow loss in clouds and statistics on cloud occurrence are presented in the companion paper by Davis (ref. 16). When the aircraft emerged from these clouds, laminar flow is regained almost instantaneously (t = 32 min.).

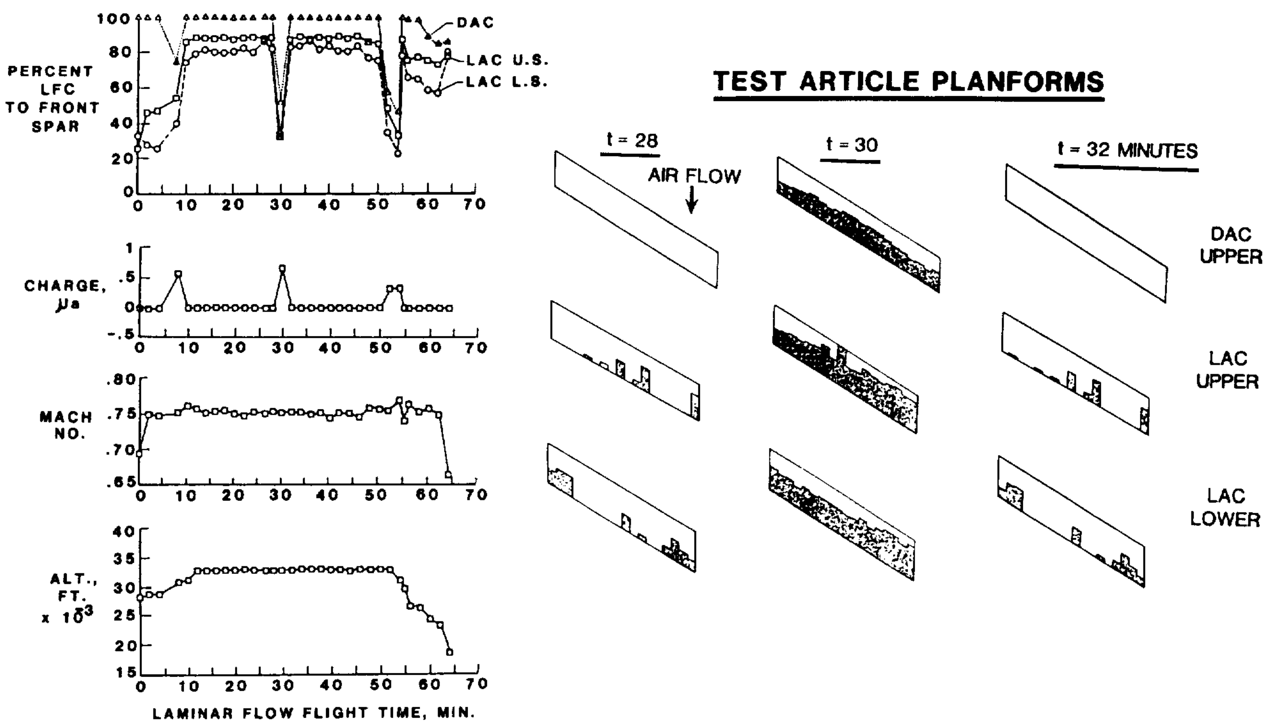


Figure 14

OPERATIONAL EXPERIENCE/RELIABILITY

Extensive flight tests were made using LFC systems located in the JetStar aircraft's leading edge region at flight conditions representative of transport airplanes in a commercial airline operational environment. LFC systems evaluated included the suction surface and ducting, insect protection, and anti-icing. A summary of the results is presented in figure 15. All operational experience was positive. No dispatch delays were encountered due to the LFC systems. There was no need to adjust suction system controls throughout the test range of cruise altitude, Mach number, and lift coefficient. Both insect anti-contaminant systems were effective in alleviating insect deposits. Non-use of the spray system on the Lockheed article during descent necessitated leading-edge cleaning between flights. Results also indicated that the supplemental spray for insect protection is not necessary for LFC transport airplanes equipped with the insect shield/high-lift device. Both anti-icing systems were effective in flight, and ground deicing was not exacerbated by the LFC systems. The system for purging the anti-contaminant/anti-icing fluid from air passages operated satisfactorily. During the simulated service in Atlanta, while on the ground the aircraft was exposed to a heavy rain of over 1.5 in. in a short time. The next day it was found that rainwater which had seeped into the LFC ducts could be successfully purged from the test article during climbout. Such results have established a preliminary maintenance and reliability data base for these LFC systems.

	PERFORATED	SLOTTED
DISPATCH RELIABILITY	GOOD	GOOD
HANDS-OFF SUCTION SYSTEM	YES	YES
ANTI-CONTAMINATION SYSTEM	SHIELD EFFECTIVE, W & W/O SPRAY	WETTING ON T.O. EFFECTIVE
LE CLEANED BETWEEN FLIGHTS	NO	YES
TEST ARTICLES/AIRCRAFT DEICED	YES	YES
ANTI-ICING SYSTEM	EFFECTIVE	EFFECTIVE
PURGE SYSTEM	EFFECTIVE	EFFECTIVE

Figure 15

TEST ARTICLE LFC PERFORMANCE (UPPER SURFACE)

Fabrication difficulties with the slotted test article internal suction system and external surface quality (ref. 5) limited the extent of laminar flow attained on this article to less than that attained by the perforated article (fig. 16). Further development of fabrication techniques for the slotted concept is therefore required. Because data were taken at one second intervals, detailed analysis is possible. Based on 20,258 data points measured during 11 flights (ref. 16), the extent of laminar flow attained on the perforated article exceeded 96 percent (cruise average to the front spar), versus 78 percent for the upper surface of the slotted article* (fig. 16). An improved surface quality on the slotted article would be expected to result in as much laminar flow as was achieved with the perforated article. Partway through the Pittsburgh simulated airline service flights, the LFC systems were used during climb and descent, as well as for cruise, and laminar flow was obtained on both test articles to altitudes as low as 10,000 feet. The amount of laminar flow achieved under these conditions was not as great as in cruise but these flights conclusively demonstrated that laminar flow could be achieved during transient flight altitudes and Mach numbers. As expected, laminar flow was lost during flight through clouds. Approximately 7 percent of the 20,258 data points were taken in clouds; this time-in-cloud result for the domestic United States is close to the time-in-cloud result of 6 percent determined as a result of a world-wide data analysis (ref. 15). No attempt was made to utilize altitude flight management in order to avoid clouds; such management would be expected to reduce the amount of time spent-in-cloud. With the exception of the inboard end of the Krueger shield, both systems for alleviation of insect deposits were effective. If the wetting anti-contamination system on the Lockheed slotted article was not used during descent, surface cleaning of the leading edge region was required before the next flight.

*The Lockheed slotted lower surface attained 73 percent laminar flow to the front spar (cruise average). Otherwise, the slotted lower surface results were the same as for the upper.

TEST ARTICLE LFC PERFORMANCE (UPPER SURFACE)

	PERFORATED LEADING-EDGE	SLOTTED LEADING-EDGE
*CLEAR AIR, CRUISE AVERAGE	~ 96% L.F. (TO FRONT SPAR)	~ 78% L.F. (TO FRONT SPAR)
CLEAR AIR, CLIMB OR DESCENT	LAMINAR FLOW TO 10,000 FT.	LAMINAR FLOW TO 10,000 FT.
CLOUDS/ICE PARTICLES	LOST LAMINAR FLOW	LOST LAMINAR FLOW
*TIME IN CLOUDS	~7%	~7%
TEST ARTICLE BUG HITS 62 FLIGHTS	~5	MANY (ON LANDING)

*BASED ON 11 FLIGHTS (20,258 DATA POINTS)

Figure 16

FLIGHT TEST SUMMARY RESULTS

Simulated airline service flight test results are summarized in figure 17.

- LAMINAR FLOW OBTAINED AFTER EXPOSURE TO HEAT, COLD, HUMIDITY, INSECTS, RAIN, FREEZING RAIN, SNOW, AND ICE
- "HANDS-OFF SUCTION CONTROLS" FLIGHTS RESULTED IN COMPLETE LAMINAR FLOW OF PERFORATED LEADING-EDGE TEST ARTICLE (10,000 FT. TO 38,000 FT.)
- LAMINAR FLOW MAINTAINED DURING MODERATE TURBULENCE
- LAMINAR FLOW LOST IN CLOUDS
- HI-LIFT SHIELD WITHOUT FLUIDS PREVENTED INSECT CONTAMINATION
- INSECT ALLEVIATION SYSTEMS WERE EFFECTIVE AND LEADING EDGES DID NOT REQUIRE CLEANING BETWEEN FLIGHTS UNLESS THESE SYSTEMS WERE NOT USED
- CONVENTIONAL GROUND ANTI-ICING EQUIPMENT SUFFICIENT FOR ICE/SNOW REMOVAL

Figure 17

CONCLUSIONS

The first JetStar leading edge flight test was made November 30, 1983. The JetStar has now been flown for more than 3 years. The titanium leading edge test articles today remain in virtually the same condition as they were in on that first flight. No degradation of laminar flow performance has occurred as a result of service. The JetStar simulated airline service flights have demonstrated that effective, practical leading edge systems are available for future commercial transports. Specific conclusions based on the results of the simulated airline service test program are summarized in figure 18.

- **LFC SYSTEMS PERFORMANCE WAS PROVEN EFFECTIVE DURING SIMULATED AIRLINE SERVICE**
- **SIMULATED SERVICE REVEALED NO OPERATIONAL PROBLEMS WITH LFC SYSTEMS AND NO SPECIAL MAINTENANCE REQUIREMENTS WERE UNCOVERED**
- **LEFT JETSTAR PROGRAM HAS ESTABLISHED THE PRACTICALITY OF BASELINE DESIGNS FOR LEADING EDGE LFC SYSTEMS FOR FUTURE COMMERCIAL TRANSPORT AIRCRAFT**

Figure 18

SYMBOLS

alt	altitude, feet
ATC	Air Traffic Control
DAC	Douglas Aircraft Company
FT	Feet
LAC	Lockheed Aircraft Company
LE	Leading Edge
LEFT	Leading-Edge Flight Test
LF	Laminar Flow
LFC	Laminar-Flow Control
NA	Not Available
PGME	Propylene Glycol Methyl Ether
SAS	Simulated Airline Service
t	time, minutes
TO	Takeoff
w	with
wo	without
μa	charge patch current, microamperes = 1 x 10E-06 ampere

<u>Airports</u>

ABQ	Albuquerque, New Mexico
ACY	Atlantic City, New Jersey
AMA	Amarillo, Texas
ATL	Atlanta, Georgia
AZO	Kalamazoo, Michigan
BAD	Barksdale, Louisiana
BGR	Bangor, Maine
BNA	Nashville, Tennessee
BOS	Boston, Massachusetts
BTV	Burlington, Vermont
CHA	Chattanooga, Tennessee
CHS	Charleston, West Virginia
CLE	Cleveland, Ohio
DCA	Washington, DC
DEN	Denver, Colorado
DET	Detroit, Michigan
DSM	Des Moines, Iowa
EDW	Edwards Air Force Base, California
GRB	Green Bay, Wisconsin
JFK	New York, New York
LFI	Langley Research Center, Hampton, Virginia
LOU	Louisville, Kentucky
MSY	New Orleans, Louisiana
OKC	Oklahoma City, Oklahoma
ORD	Chicago, Illinois
ORF	Norfolk, Virginia
PIT	Pittsburgh, Pennsylvania
RDU	Raleigh-Durham, North Carolina
RIC	Richmond, Virginia
SPI	Springfield, Illinois
STL	St. Louis, Missouri
TPA	Tampa, Florida
TYS	Knoxville, Tennessee

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